# STREAMLINING COLLABARATIVE PLANNING IN SPACECRAFT MISSION ARCHITECTURES

**Dharitri Misra ([a]), Michel Bopf ([a]), Mark Fishman ([a]),**
**Jeremy Jones ([b]), Uri Kerbel ([a]), Vince Pell ([a])**

**([a]) AppNet Inc., Laurel, Maryland, 20707, USA**
**([b]) NASA Goddard Space Flight Center, Greenbelt, MD 20771**

**ABSTRACT**

During the past two decades, the planning and scheduling community has substantially increased the capability and efficiency of individual planning and scheduling systems. Relatively recently, research work to streamline collaboration between planning systems is gaining attention. Spacecraft missions stand to benefit substantially from this work as they require the coordination of multiple planning organizations and planning systems. Up to the present time this coordination has demanded a great deal of human intervention and/or extensive custom software development efforts. This problem will become acute with increased requirements for cross-mission plan coordination and multi-spacecraft mission planning.

The Advanced Architectures and Automation Branch of NASA's Goddard Space Flight Center is taking innovative steps to define collaborative planning architectures, and to identify coordinated planning tools for Cross-Mission Campaigns. Prototypes are being developed to validate these architectures and assess the usefulness of the coordination tools by the planning community. This presentation will focus on one such planning coordination tool, named Visual Observation Layout Tool (VOLT), which is currently being developed to streamline the coordination between astronomical missions

**Keywords:** coordinated observation, planning collaboration, visual planning tools, multi-platform coordination

## 1.0 Introduction

The Advanced Architectures and Automation Branch of NASA's Goddard Space Flight Center, for the past few years, has been active in the arena of collaborative planning. The initial work resulted in two independent studies: the first one was the Cooperative Autonomy Project that explored how multiple spacecraft could collaborate to achieve a common goal. The second study, the Collaborative Advanced Planning Environment, investigated ways to provide scientists with 'transparent' access to mission resources, reducing the perceived disconnection between a scientist's plan and mission execution of that plan. These studies resulted in the following common conclusions:

1. Scientists are isolated from the execution of their plans
2. Replanning is a time-consuming and intensely manual process
3. Current planning systems are inadequate to address the needs of upcoming mission architectures, such as constellations and cross-mission collaborations.
4. There are not enough tools available for the scientists to receive feedback on the efficiency or schedulability of their plan.

***The ComPASS System***

Based on these studies, a prototype scientist-to-spacecraft planning framework, called the *Common Planning And Scheduling System (ComPASS)*, was developed. It provides a *vertical collaboration architecture* that facilitates the collaboration between scientists, mission engineers and mission operators through a multi-fidelity, multi-level planning framework. Instead of one monolithic planning system with an integrated, complex planner/scheduler, the framework allows for several islands of planning, one at each plan level, using appropriate planners for that level. The output of the planner at each level can be analyzed, modified, replanned and finally fed as the input to the next level. This results in early identification of problems and user feedback that helps in a quick replanning process.

A prototype implementation of ComPASS was done in 1998-1999 to demonstrate the science planning capability using plug-in external scheduler into the system. A science level plan was generated from the ComPASS framework using an observation planning tool called the Scientist's Expert Assistant. This plan was then processed by an external Scheduler called ASPEN (developed by the Jet Propulsion Laboratory) to generate a higher fidelity mission level plan for the system. A set of Mediators and an internal plan representation (through a common plan language named CPL) facilitated in adapting different external tools and planners into the system in a seamless manner.

***The VOLT System***

Although powerful in concept, and applicable to a large variety of missions, ComPASS is too generic and too ambitious a project, which needs a multi-year development and testing cycle to be acceptable operationally. In the meantime, with the advent of Constellation missions and Virtual Platform concepts, the need for horizontal planning collaboration among multiple spacecrafts was evident. From our experience with other studies and interaction with planning coordinators and scientists, the lack of advanced tools to help in collaborative planning and in determining the schedulability of such plans was felt strongly. Thus, the ComPASS team focused their attention on the development of a planning coordination tool called the *Visual Observation Layout Tool (**VOLT**)*, which applied many innovative approaches used in ComPASS.

Presently, the first prototype of VOLT is being developed to facilitate collaboration between astronomers who want to coordinate their observations on different astronomical observatories, as well as to determine the schedulability of their coordinated or stand-alone observations. The advantage of VOLT over other such tools that may exist currently is that VOLT retrieves the planning information, presented to the users, from the individual mission's planning/scheduling facility wherever possible, thereby assuring maximum consistency possible.

For the future, VOLT aspires to apply its modular architecture and configurable design to develop enhanced tools to facilitate coordinated planning for Virtual Platforms, as well as for Constellations, where the end user could be a scientist, a mission operator or an autonomous on-board planner.

The rest of this paper describes the first prototype of the VOLT system, developed in concert with the Space Telescope Science Institute (STScI), to help in the coordination of astronomical observations among collaborative observatories. First, it presents the current process of planning coordination and justifies the need for advanced visual tools. It then discusses the objective and architecture of VOLT to illustrate its usefulness as such a coordination tool.

## 2.0 Overview of Planning Coordination for Astronomical Observations

Each year, a number of proposals are accepted by a space-based observatory for conduction of astronomical observations and gathering of science data for the study of galactic events – in different energy regions of the electromagnetic spectrum. Often, targets need to be observed in multi-wavelength regions or for studying time evolution of interesting astronomical phenomena - such as interacting binary systems, the oscillations associated with Novae, as well as for the study of planets, comets, flare stars and gamma ray bursts These studies also helps in developing more realistic physical models. The underlying observations need to be conducted simultaneously or through temporal coordination.

Since each space-based observatory uses a set of instruments designed to operate in specific energy regions, most such studies are conducted by submitting observation proposals to multiple observatories, with request to coordinate among themselves. The number of such coordinated proposals have increased due to new innovations in observatory coordination, including trading telescope time (as Chandra and HST have) so that one observatory can award coordinated time between two telescopes.

Many conditions/constraints need to be satisfied for proper scheduling of any requested observation. In addition, scheduling of coordinated proposals requires elaborate manual collaboration between the planning coordinators at each observatory, to assure that they can be observed after meeting all the related constraints. The following subsection explains how a proposal is typically processed in a facility, and why automated tools are useful to both scientists and coordinators for successful scheduling of proposals.

### 2.1 Proposal Processing Scenario

After a proposal is received in an observatory, it undergoes a number of processing steps, performed by the coordinator, before it is ready to be included into the long range planning request set. This processing includes not only the decomposition and validity checking of the proposal, but also the evaluation of its schedulability by different in-house tools.

The following figure provides an example of a proposal-processing scenario for a queue-based astronomical observatory

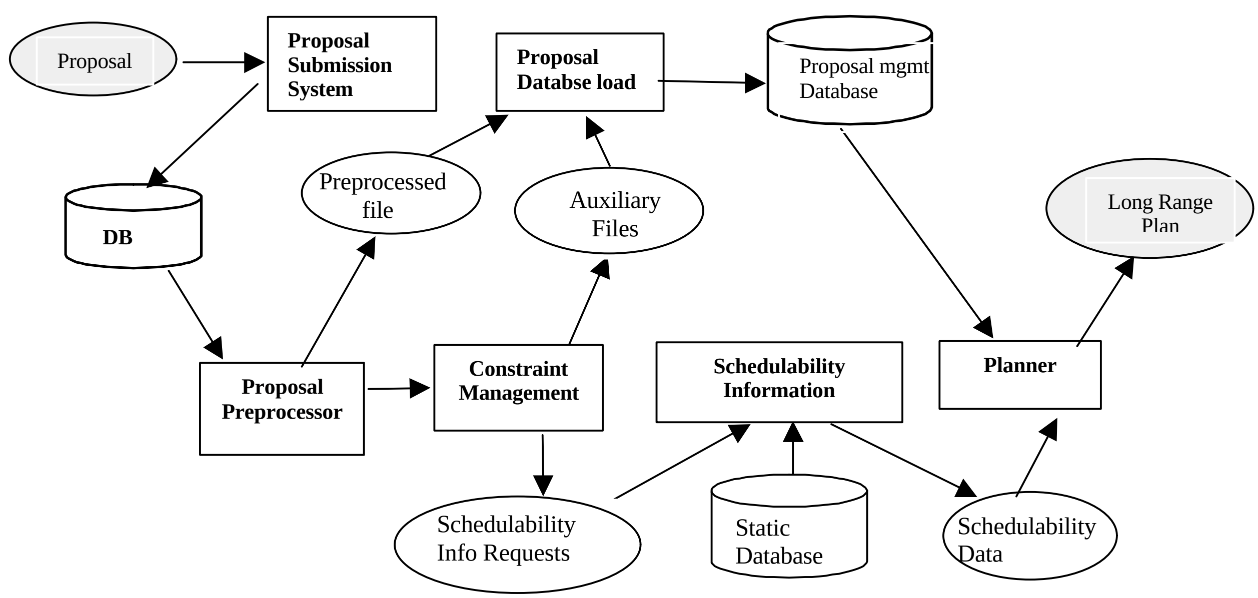


**Figure 1 – A Sample Proposal Processing Scenario in an Observatory Facility**

For coordinated observations, iterative changes to the proposals are often performed by the coordinators and the observers manually until satisfactory results are assured. Only then are the proposals sent to the scheduler for incorporation into a long or short-range schedule. Obviously, these are arduous and time-consuming processes, in which neither the observers nor the program coordinators are confident of the outcome until very late.

### 2.2 Difficulties in Manual Coordination and Need for Automated Tools

Presently, there is a lack of automated tools for planning coordinators to check the schedulability of a coordinated observation, *requested for a different mission*, from their local institutes. Each coordinator is expected to run the proposal, determine its schedulability and then inform the coordinator of the collaborating mission to perform similar steps in parallel. Then manual comparisons have to be made by the coordinators to determine if the observations were schedulable as a set within the allowed time windows. The proposals may have to be modified by either one or both of them, in agreement with their respective observers and the whole process has to be iterated several times before satisfactory results are achieved. Needless to say, this is a slow and error-prone process.

Hence, it is beneficial to provide a set of visual tools to the coordinators as well as the observers, which would enable them to check the schedulability of their plans from their local institutes. These tools should also help them to refine the plans in early stages such that coordinated observations can take place more easily.

### 2.3 Basic Schedulability Terminologies

In order to present the detailed functionalities and architecture of the VOLT system, the meaning of the following basic terminology need to be explained here.

- **Schedulability of an Observation**

Schedulability indicates when a specific observation is possible in accordance with the orbital characteristics and inherent constraints of the system, as well as due to constraints imposed upon by the observer to meet their science requirements. Examples of such constraints for a low earth orbiting observatory are: orbital viewing restrictions due to earth occlusion, exclusion due to South Atlantic Anomaly, Guide Star availability, Roll angle restriction for the operation of certain instruments, as well as temporal constraints related to another planned observations.

- **Schedulability Timelines**

For a given observation, schedulability data consists of dates and times (time windows) within the observation cycle at which the observation may be scheduled without violating any specified constraint. This timing information is referred to as the Schedulability timeline. In general, each constraint specifies its own timeline. For certain constraints, such as Guide Star availability, each schedulable time window may show its variation in schedulability within the window with a “quality of fit” indicator.

- **Mission Schedulability**

Mission Schedulability indicates the schedulability of an observation within a given mission. This comprises of the set of time intervals during which each schedulability constraint is satisfied. In other words, it is computed by merging the individual schedulability for mission-specific constraints (that is, it is computed from the intersection of these individual timelines). The user may associate weighting factors with each constraint to study change in schedulability of an observation during the scheduling cycle.

- **Coordinated Schedulability**

This refers to the possibility that an observation may or may not be schedulable in conjunction with some other observations upon which it depends. It is often possible that each observation may be schedulable by itself - by satisfying its mission-specific constraints, but cannot satisfy the temporal or other constraints that indicate the criteria of coordination. Coordination schedulability of an observation is therefore determined from individual mission schedulability data through the satisfaction of coordination constraints.

- **Constraint Relaxation**

It is possible for the scientists to relax certain constraints imposed upon their observations or the coordinated observations such that an observation would become schedulable although it failed to do originally. The schedulability factor of an observation may also be improved by experimenting with these constraint specifications and selecting the most suitable conditions. However, to do so, the users (both the scientists and the planning coordinator) require visibility into an observation's Schedulability Timelines and detailed information on how each constraint affects the schedulability of the specific observation.

## 3.0 VOLT Objectives

The primary objective of VOLT is to bridge the gap in the coordinated planning arena of science missions by providing the scientists and planning coordinators visual tools, which would help them for better science planning. Specifically, it would help enable them to:

- Check the schedulability of an observation in the context of its host observatory, along with that of the coordinating observation(s) by the collaborating mission(s), and find the areas of overlap, indicating feasible time windows.
- Check the actual schedule of each observatory within a requested time interval covering the observation.
- Provide feedback on the constraints on the observation, imposed both from science, and from mission health and safety perspective, that limit the schedulability of the observations. Help the users to relax these constraints, if permissible, for improved results.
- Make these tools configurable for use by different categories of users, namely the observers, the coordinators at a local observatory, and the coordinators at a collaborating observatory.

VOLT intends to take advantage of the many scheduling tools already provided by individual observatories, and to support "what if" scenarios to help in effective replanning of observations.

## 4.0 Initial VOLT Prototype

The first VOLT prototype, currently under implementation, is intended to provide visual tools to help automate the planning of coordinated observations by multiple astronomical observatories, such as the Hubble Space Telescope (HST), Chandra X-ray Observatory (Chandra or AXAF), Far Ultraviolet Spectroscopic Explorer (FUSE), and the Rossi X-ray Timing Explorer (RXTE). A related goal is to provide better visibility into planning information for improving the schedulability of a stand-alone observation for any of these observatories.

Although the initial prototype will support only a specific set of space-based observatories, it should be easily extensible to other missions and queue-based ground observatories in future.

### 4.1 VOLT System Architecture

In order to accomplish the above stated objectives, the VOLT system is being developed as a flexible framework consisting of two major components:

(a) A front end component that interacts with the user to receive observation specifications, and provides visualization capability for scheduling and related information
(b) A back end component that may be configurable to interface with an observation data source such as the proposal, and an observatory's planning and scheduling system from where it retrieves relevant information to be presented to the user. In the event is it not feasible to obtain the schedulability data from an observatory facility in a modular fashion, VOLT can interface with a specified external facility that provides the required data with reasonable degree of accuracy.

The external VOLT system interfaces are shown in Figure 2.

If an observation is being coordinated with one or more other mission observations, VOLT is capable of querying all the associated facilities and presenting the mission/coordinated schedulability information on the same output screen in a visually meaningful way. The details of how VOLT interfaces with an external facility for getting different components of scheduling data are presented schematically in the Use case diagram of Figure 3.

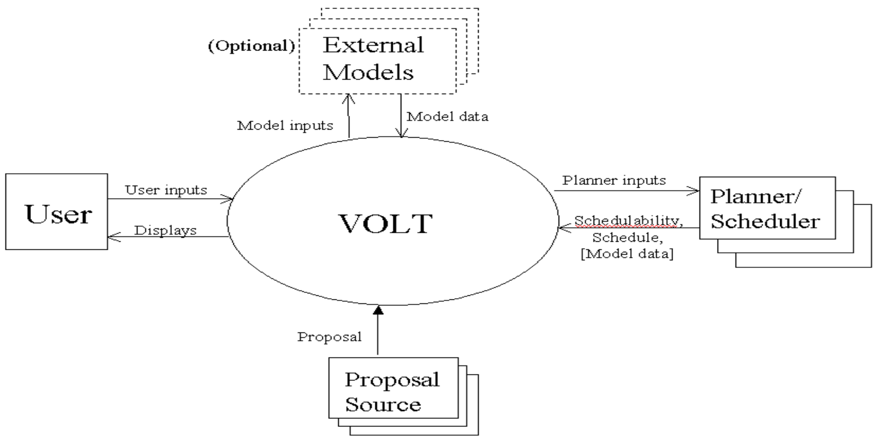


**Figure 2 – VOLT External Interfaces**

In Figure 3 the VOLT system and each Planning/Scheduling system (SCH) is represented by an Actor, and each bubble represents a use case (UC-x.y.z) showing the interface between the Actors. The notation (1-n) indicates that simultaneous connection to 1…n such systems is feasible.

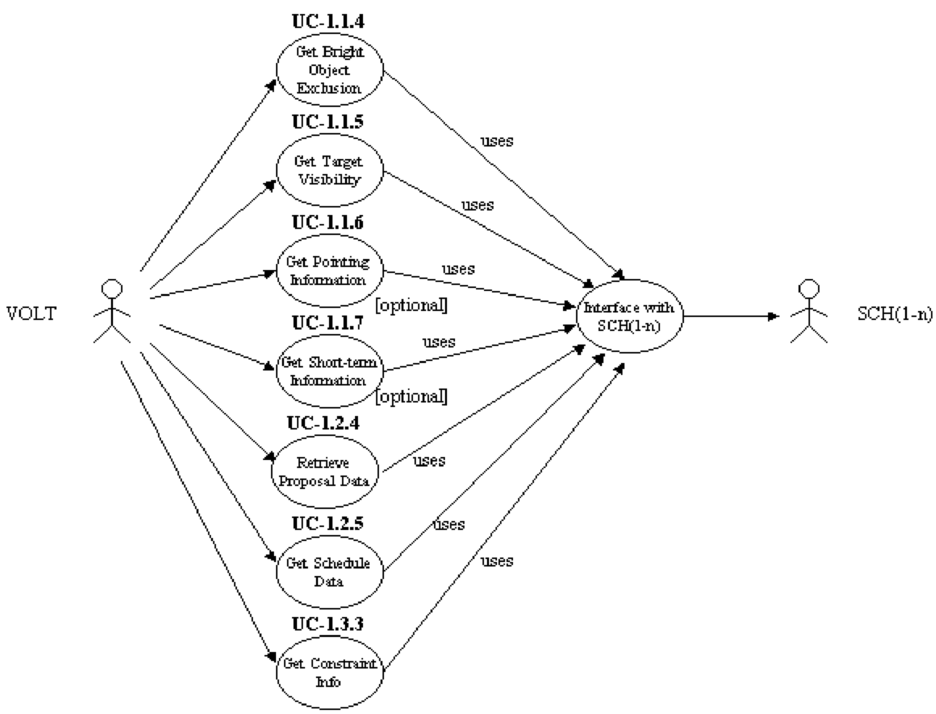


**Figure 3 - VOLT Interaction with External Facilities**

It is important to note that for VOLT to connect to a Planning/Scheduling system and conduct its queries, the facility must provide reasonable external interfaces such as file-based or Program Interface based interfaces.

### 4.2 High Level System Design

The front and back end components of the VOLT system are represented by two separately executable processes, known as the VOLT Client and Server processes respectively, with the latter providing a configurable gateway for the external planning facilities. The two components communicate with each other through remote calls. The VOLT server interfaces with each Mission's planning facility through a Mediator object, which transforms the client request to observatory-specific queries, and formats the Observatory provided data and timelines into VOLT-specific internal representation. The Client performs visual rendering of this data and presents it on the screen in the form of display panels.

The following sections discuss and present some display screens or panels used by VOLT for receiving user input and for providing visualization of schedulability data. VOLT being in the early phase of development at the time of this writing, we expect that these displays and layouts to evolve and change as the system matures.

### 4.3 Specification of Observations and Coordination Criteria

VOLT may be used as a planning tool to study the schedulability of coordinated as well as individual observations. The user interface provides this flexibility, in which the user may specify a target and select one or more missions under which it would be observed. This is shown in the left hand diagram in Figure 4. The user may then indicate coordination between these observations by linking them and specifying desired temporal constraints between them. The right hand diagram shows the coordination specification for observing a target simultaneously under three different observatories: HST, FUSE and Chandra.

Note that VOLT would also support the retrieval and display of observations from already submitted proposals and help modification of these proposals for better schedulability. It is expected that the former scenario would be more useful to the scientists in the original planning, where as the second one is for use by both the planning coordinators and the scientists for iterative changes.

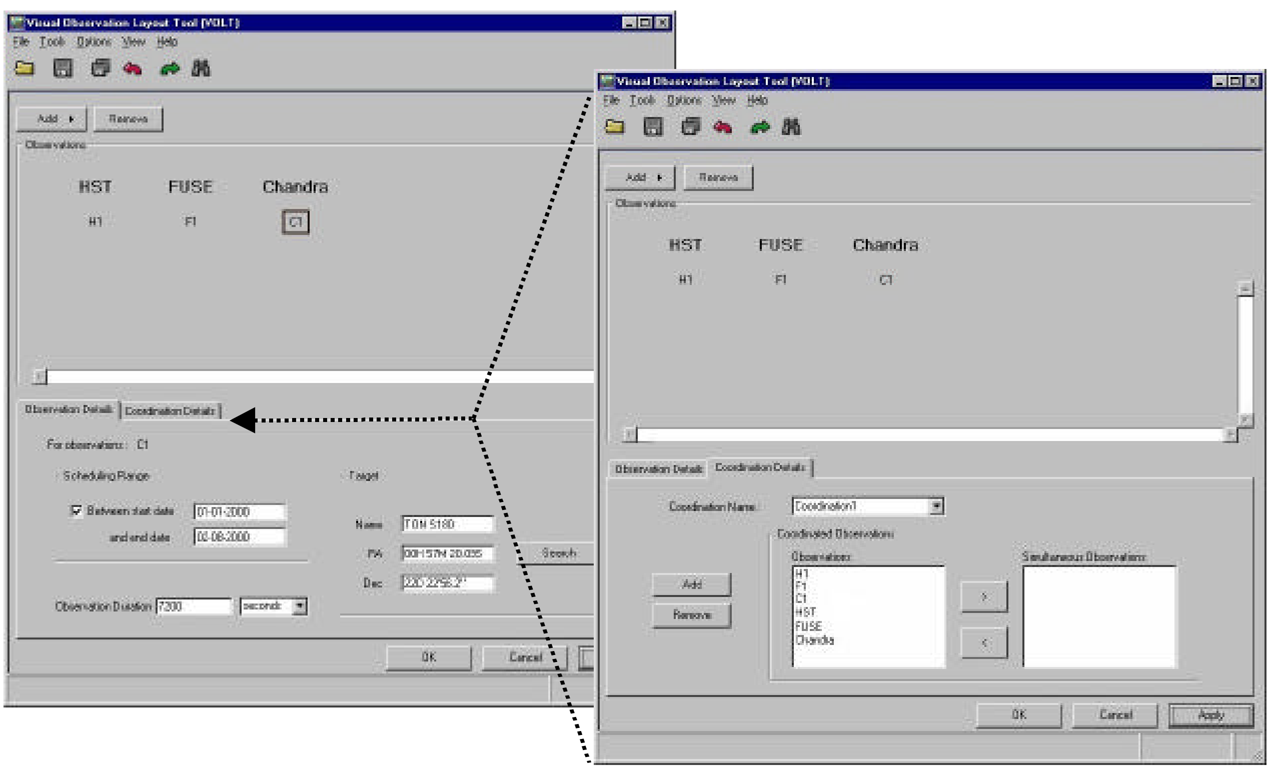


**Figure 4 - Observation and Coordination Specification Panel**

### 4.4 Visualization of Schedulability Data

Schedulability information for a set of coordinated observations is presented in a hierarchical tree format in the VOLT Schedulability Display Panel, shown in Figure 5. At the highest level, a coordination timeline for each observation is presented on the screen. The user may click on each of these lines to display the corresponding Mission timeline of the observation. Similarly, a Mission timeline may be further expanded to display the underlying timelines corresponding to each selected schedulability attribute such as Guide Star availability, SAA exclusion, and Roll.  A tooltip capability is also provided to explain the user why a certain time gap along a timeline is not schedulable.

VOLT provides the capability for the user to select any schedulable time window for an observation as the one to be used for scheduling. When this selection occurs for a coordinated environment, VOLT indicates the windows that are no longer selectable (as they would violate the coordination constraints) for other observations. This feature is useful when the coordinated observations are not simultaneous.

Once the user selects a certain time window for a specific observation, the request may be submitted to the Planning system for incorporation into a schedule and provide feedback. The schedule information may then be displayed on the panel along with the corresponding schedulability data.

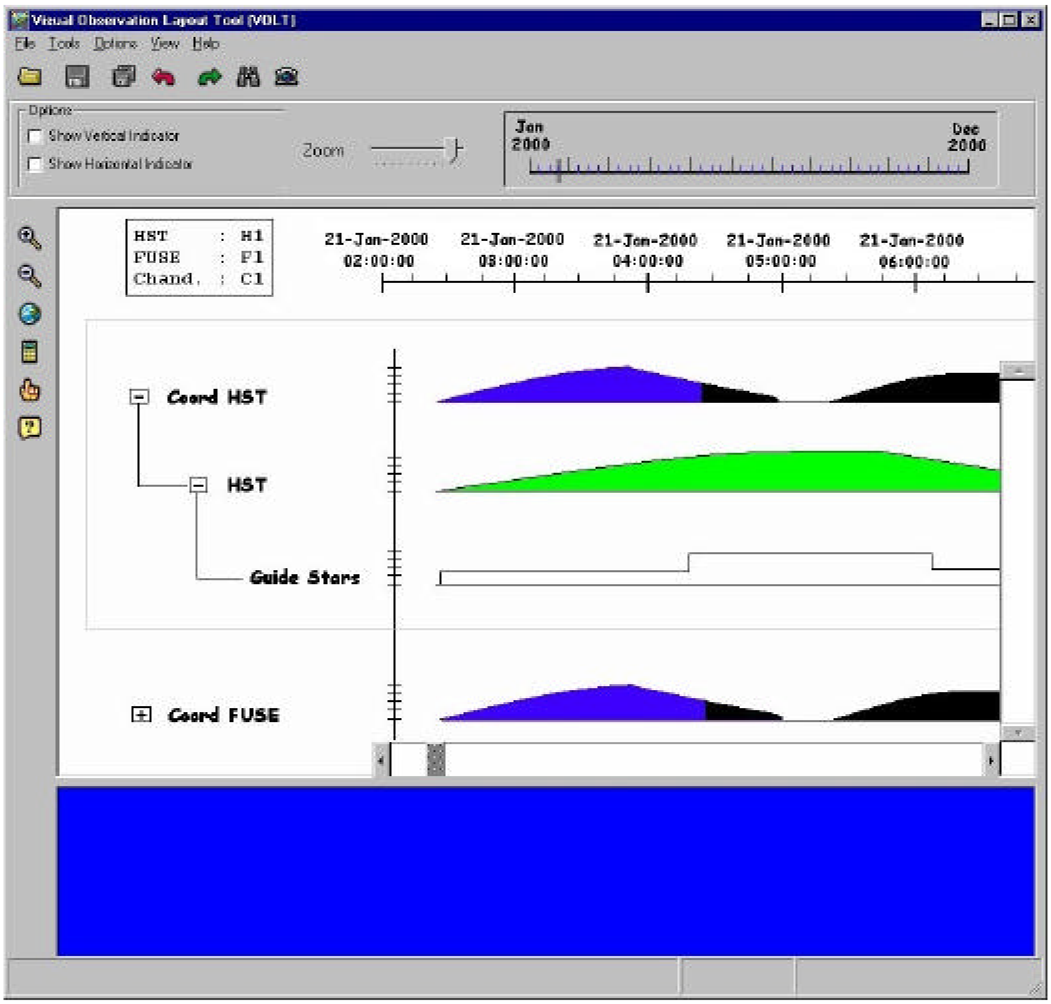


**Figure 5 – Hierarchical Presentation of Schedulability Timelines**

### 4.5 Integration With Other Planning Tools

Often, the users use domain-specific planning tools to help determine the specifics of their science observations (such as the target, instrument, duration, etc.). For convenience, VOLT is designed to be integrated with such tools if they provide suitable integration hooks. Currently, VOLT may be run from the Scientist's Expert Assistance (SEA), a prototype observation specification system for the Next Generation Space Telescope (NGST). In the future, VOLT may also be integrated with the Astronomer's Planning Tool (APT) system for the Hubble Space Telescope. However, VOLT may also be run in a stand-alone environment with its full functionality.

## 5.0 Future Enhancements

The VOLT prototype, in its final phase of development would provide useful feedback to the user on how the proposal might be modified to improve the "quality of fit" of the observation. In future, it may also assist the user in changing the constraints to improve the "quality of fit" and save the modified proposal after changes are made. Integration of Expert system technology may be required to provide such assistance.

Furthermore, while support for the Space Science missions presented above is VOLT's short-term goal, its flexible architecture will enable VOLT to easily adapt to other planning environments including:

- Multi-mission Virtual platforms
- Ground-based observatories
- Earth Science Missions
- Sensor Web (Multiple spacecrafts observing the Solar System in concert)

## 6.0 Acknowledgements

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